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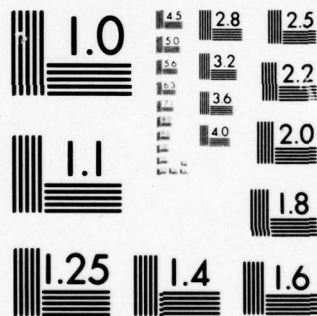
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Step-Through Simulation:

A METHOD FOR
IMPLEMENTING DECISION ANALYSIS

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J. W. Ulvila
R. V. Brown
L. S. Randall

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STEP-THROUGH SIMULATION:

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J.W. Ulvila
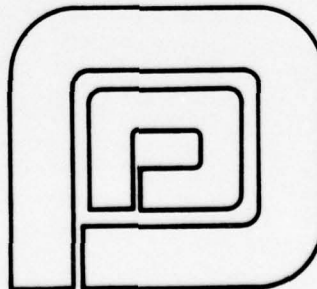Harvard University
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the initial development of the Step-Through variant of Monte Carlo simulation, a new procedure for implementing decision analysis or for training decision makers.

Like regular Monte Carlo simulation it involves sampling possible aftermaths of an initial action, and generating a distribution of outcome values for it. However, the detailed structure and/or assessments of the decision model are →next page

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elicited <u>as called for</u> in the execution of each trial. It therefore permits substantial economy of elicitation if there are few trials. The Step-Through procedure also offers economy of elicitation and calculation over a traditional extensive-tree decision-analytic model without requiring simplifications or aggregations in the model's conceptualization.

In addition to describing this procedure, this report illustrates its use in the context of a Navy task force commander's decision situation, describes a prototype interactive graphic computer implementation of this procedure, and presents the results of a preliminary test and evaluation of it.

SUMMARY

The standard form of decision analysis, typified by the
rollback of an extensive decision tree, involves the complete
definition and assessment of sequences of acts and events,
from which a probability distribution of values and/or an
expected utility for each initial option can be derived.
When applied to real decision problems, however, it often
results in models that are either too complex or too simple.
The complex models are unmanageable to elicit. Simple
models may call for a high degree of judgment aggregation
(though the subject's judgment bears more usefully on the
detailed texture of the problem) or, alternatively, simple
models may require inappropriate simplifying assumptions.

Conventional Monte Carlo simulation substantially
reduces the computational chore of the more complex structures,
but not the elicitation requirements. The Step-Through variant
of Monte Carlo simulation also seeks to maintain the structural
form (and essence) of an extensive tree but drastically
reduces the number of required elicitations as well as calcu-
lations.

Like conventional Monte Carlo simulation, the Step-
Through variant uses a random sampling procedure to generate
a sample of trials or paths through a decision tree, from
which the probability distribution of all possible outcomes
to (and values of) any given action or strategy is estimated.
Unlike conventional Monte Carlo simulation, it does not
require the user to define completely the more extensive tree
that underlies it or to specify all the probabilities called
for. Instead, each segment of the decision tree is specified
only when and if required <u>for the trial in question</u>, including
the listing of acts and events and the assessment of proba-
bilities. Subsequent acts may be assigned according to a

preset strategy which is to be evaluated, or selected on-line by the subject, or even treated as an uncertain event to be sampled. The elicitation is thus on-line, dynamic, selective and, provided the trials are few in number, economical of effort. A special, limiting case is Modal Step-Through, where a single path is generated, and at each step the most likely sequel is selected; this is particularly easy to apply.

Nevertheless, many of the seemingly irreducible problems of eliciting complex act-event structures remain with Step-Through, which discourages absolute reliance on any complex personalist model (that is, a model of a specific subject's thinking) for action selection. Simpler models such as the direct-probability assessment of dimensions of value may generally be preferred unless the stakes involved are very high.

The main value of Step-Through may, indeed, be as an auxiliary decision aid. For example, a few trials can be run to sensitize the subject (decision maker) to the kind of consequences a decision may have. Then he may make the decision informally or make the assessments needed for a simpler decision-analytic model. Modal Step-Through is often sufficient for this purpose. Alternatively, Step-Through can be used for generalized training of decision makers, as a kind of war-game in which initial and subsequent acts are chosen by the trainee and other elicitations are provided by other players.

This paper describes the Step-Through variant, illustrates its use in a Navy task force commander's decision situation, describes a prototype interactive computer graphic implementation, and presents the results of preliminary tests of its viability. It consolidates and expands upon earlier

developmental work on this topic performed under the sponsor-
ship of the Office of Naval Research and the Rome Air Develop-
ment Center.

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FIGURES

ACKNOWLEDGMENTS

1.0 INTRODUCTION TO STEP-THROUGH SIMULATION

1.1 Motivation for Step-Through Simulation

1.1.1. As a complete action selection device - In the
standard, classical use of decision analysis to model a
decision maker's action selection problem, the extensive-form
tree, all relevant elements of the situation are modeled
explicitly in a decision tree. That is, all of the decision
maker's initial options and their subsequent event and
action implications are displayed in a decision tree, a
probability is assessed for the occurrence of each event, and
a value is assigned to each path through the tree. On the
basis of these assessments, each option can be evaluated by
taking a weighted average value, by "rolling back" the tree.[1]
It should be noted that there are many acceptable alternative
formulations within this mold, differing, for example, in how
finely events are defined and therefore how complex the tree
is. For convenience, we will reserve the term "extensive
tree" for the more complex formulations.

This use of decision analysis is conceptually very
appealing, for it provides for the maximum amount of disag-
gregation of the problem into manageable sub-problems. How-
ever, in practice, an explicit model of all relevant elements
of a decision problem often requires an unmanageably large
and complex assessment task, sometimes involving millions of
assessments. In addition, the computational demands of a
complex extensive-form decision tree are very large.

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[1]See Brown, Kahr, and Peterson (1974); Raiffa (1968); Schlaifer
(1969); or Handbook for Decision Analysis (1973) for a fuller
description of the classical use of decision analysis.

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Variants of this classical paradigm have been sought in an attempt to overcome the computation and elicitation burdens of the complex extensive-form decision model. Some of these variants include: direct-value model, direct-probability model, and staged-tree model.[2]

The direct-value model is a very simple one that models the value of the initial options explicitly but considers uncertainties and subsequent action choices only implicitly. In a direct-value model, each option is evaluated along one or more dimensions of value, and a trade-off function is specified to allow the resulting values to be aggregated into a single index of attractiveness. Uncertainties and subsequent actions are taken into account implicitly in deciding the values of each immediate option. The direct-value model greatly reduces the amount of both elicitation and computation required by an extensive tree, at a cost, however, for the direct-value model often requires assessments that are very difficult to make. That is, by requiring evaluations that implicitly consider the uncertainties and subsequent actions, the direct-value model aggregates the entire path following an option. This procedure works well for fairly simple decision problems in which, although consideration of trade-offs is crucial, there are no critical uncertainties. However, in complex decision situations, this aggregation may lead to assessments that are grossly inaccurate because the implicit considerations are so difficult to make. The point is that everything which might occur after the action must somehow be reflected in the values assigned (one value for each criterion) to the action.

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[2]See Brown, Hoblitzell, Peterson, and Ulvila (1974) for a fuller description of these variants.

Similar to the direct-value model in its simplicity is the direct-probability model, where probabilities are assessed explicitly for key uncertain events that directly contribute to the outcome. This variant only implicitly considers multiple-value criteria, subsequent action choices, and events that are informational rather than directly contributing to value. A direct probability model works well in simple decision situations in which uncertainty, rather than value, is the main consideration and determinant of a good decision. However, in complex decision situations, the direct-probability model, like the direct-value model, does not allow for the amount of disaggregation required to make accurate input assessments.

The staged-tree variant is representative of a class of variants that force the decision problem to take a special form. The staged-tree variant assumes that all of the relevant information in an extensive-tree model of a decision problem can be represented in a series of summary state descriptions. The decision tree can then be replaced by a concatenation of Markov models. This special form greatly reduces the complexity and computational burden of the extensive tree but at the expense of introducing stochastic independence assumptions that are not easily met in practice. In addition, the staged-tree and other related variants do not permit the convenient disaggregation that is permitted in the extensive-form tree.

All of the simplifications of the extensive form mentioned above are effective in reducing the number of elicitations and the amount of calculation needed in a large extensive-form model. However, none of these methods maintains a very desirable feature of extensive form, that of disaggregating a complex decision problem into a series of sub-problems that

are easy to manage. One way to reduce the computational burden of the extensive-form analysis while maintaining its disaggregation is to use conventional Monte Carlo simulation to sample paths through an extensive tree, which has been completely specified, to obtain a distribution of end positions for each immediate action alternative. This method allows for the same degree of disaggregation as the extensive-form tree, but it also requires the same number and types of elicitations. Thus a gain is made only in the amount of computation required; the assessment burden is the same as that for an extensive-form tree.

The problem remains to find a modeling technique that allows for a reduction in the number of elicitations and the amount of calculation required by a complex extensive-form analysis but retains the disaggregation advantage that an extensive-form tree offers for complex decision situations. The Step-Through variant of Monte Carlo simulation approach appears to have these features.

1.1.2 <u>As an auxiliary decision aid</u> - In addition to providing a complete analysis of alternative options leading to a clear prescription for action, a desirable analytic tool may have other functions:

o   To organize and sensitize a subject's perceptions
     of a decision problem so that he can more readily
     make an <u>informal</u> decision, or provide input to some
     other decision model. Some structured exploration
     of detailed possible sequels to a decision may make
     it easier to make broad aggregated assessments of
     major summary outcomes, as needed for a direct-
     probability model, and

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o   To train and/or evaluate a tactical decision maker
      by giving him vicarious experience in responding to
      a rapid succession of uncertain contingencies
      flowing from some initial action. War gaming has
      exactly this function, but its conventional forms
      often lack a satisfactory probabilistic mechanism.

1.2 Description of Step-Through Simulation

The logic of the Step-Through variant is essentially
that of conventional Monte Carlo simulation. That is, Step-
Through involves simulating paths through an implicit extensive-
form tree in order to obtain a sample of endpoints for each
initial option. Unlike conventional Monte Carlo simulation,
however, Step-Through requires assessments of inputs as a
trial progresses in an interactive procedure which alternates
assessments with Monte Carlo sampling of events in chrono-
logical sequence, rather than a complete specification of all
inputs in advance. In this manner, many of the tree paths
that have a low probability of occurrence will never be
sampled and thus will never need to be modeled.

A process diagram of the Step-Through procedure is shown
in Figure 1-1. The procedure is begun by the decision
maker's choosing an option from among those immediately
available. Next, the following node in an implicit decision
tree is defined. If this node is an event node, Monte Carlo
simulation is used to choose a branch of the node, and this
simulates a result at the node. If this node is an action
choice node, however, the decision maker chooses the branch
to follow. Nodes are processed in this manner until a
complete path through the tree has been simulated. Then
other paths are simulated, in a like manner, for the same
option, thus generating a sample of endpoints for the action.
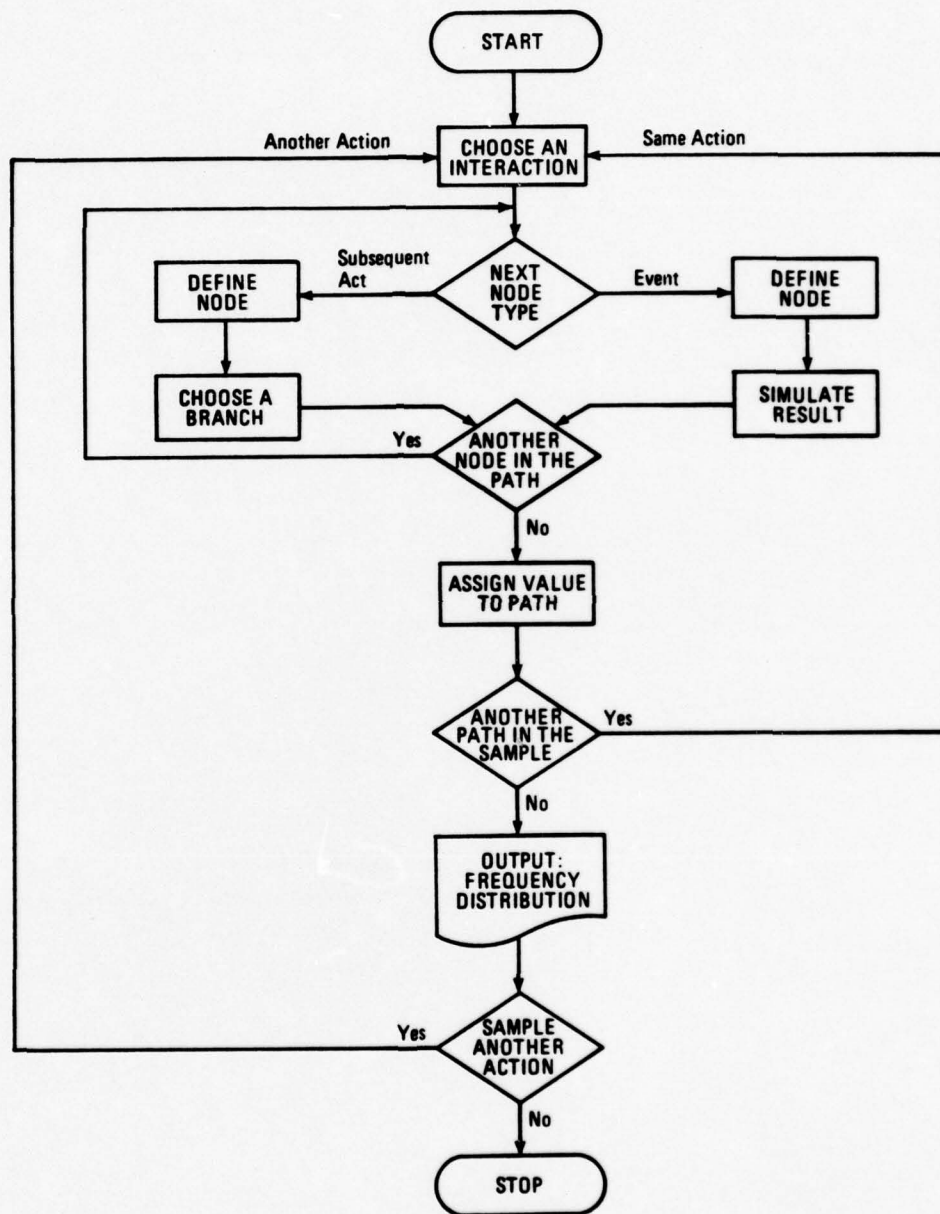
Figure 1-1

PROCESS DIAGRAM OF STEP-THROUGH SIMULATION

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The same procedure is then repeated for each initial option. After paths have been sampled for all initial options and their endpoints valued, their frequency distributions of values are compared to determine the best choice. (The valuation may be direct, through the assignment of a single value to each path, or indirect, through the combination of multiple dimensions of value).

The resulting samples of endpoint values are interpretable in the same way as those for conventional Monte Carlo simulation. However, Step-Through offers a reduction of effort and a flexibility not available in conventional simulation: the total number of required assessments is fewer (since assessments are required for only the paths actually encountered in this simulation), and the structure of the tree itself can be developed as the trial progresses. At the analyst's option, subsequent acts can be consciously chosen as they occur, specified as elements of a predetermined strategy, or treated as uncertain events.

A special abbreviated form of Step-Through, which can be used as a preparation for the more general case (or indeed for some other form of decision analysis) is Modal Step-Through. For this, a single trial is generated for each initial action. However, instead of eliciting a complete probability distribution for each uncertain event called for and randomly sampling a value from it, the most probable, or modal, event is judgmentally selected. This procedure will not, of course, give any measure of uncertainty about the total value of an initial action; but it is very easy and inexpensive to do and may be most suggestive of the best way to proceed with the analysis, possibly by some technique other than full Step-Through. Modal Step-Through may also be very useful in training, or at least preparing, the subject for the elicitations he may be called upon to pro-

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vide. For example, this form has occasionally been used to
precede the direct-probability form of decision analysis,
which appeared to benefit from having had the subject address,
however briefly, the detailed texture of possible aftermaths
to the initial actions.

Software for a prototype interactive graphic computer
program to implement Step-Through is described in the Appendix
to this report, together with instructions on how to use it.

1.3 Number of Trials Needed for Step-Through Simulation

As with other kinds of Monte Carlo simulation, the
number of trials must be sufficient for the sample to adequately
resemble the implicit population of paths from which it is
drawn. However, the issue is particularly crucial here
because of the exceptionally high variable cost per trial.
More than a few trials will soon offset the savings in fixed
cost compared with conventional Monte Carlo simulation.

It might be thought that the expected sampling error of
estimates would be related to the length of the path; it
might therefore be inferred that using Step-Through to model
a decision problem with long paths requires an unreasonably
large sample of paths. A closer examination, however, shows
this concern to be unwarranted.

Since Step-Through is a procedure for drawing a random
sample from a target population (in this case, the target
population is the value of endpoints in a decision tree),
the rules of error for sample statistics apply. These
rules, however, state that the sampling errors of the statistics
depend only on the type of sample (for instance, a random
sample, a stratified sample, a systematic sample, and so

forth), the sample size, and the underlying distribution of the target population. The sampling errors do not depend upon the complexity of the model used to represent the target population.[3] For example, in the language of classical inference, the standard error of a random sample from a normally distributed population is equal to the standard deviation of the population divided by the square root of the sample size. The standard deviation of the population, in this case the target variable, is the same whether the sample of size n is drawn by means of a single-tiered model (such as a direct probability model) or a many-tiered model of the same target variable (such as would be involved in an ambitious simulation). For personalist, or Bayesian, inference, an analogous argument can be made in terms of likelihood functions and priors. The general argument does not depend on the parent distribution's being normally distributed.

Thus, increasing the complexity of a model of a target variable does not, of itself, affect the distribution of that target variable it is attempting to model and therefore has no effect on the sampling error of estimates of the population's parameters.

This argument applies equally well to conventional Monte Carlo simulation, though it is by no means universally acknowledged by practitioners of that art, and we have not seen it presented in the technical literature.

Although greater model complexity does not call for a greater number of simulation trials, the modeling error inherent in a model of the target variable may be reduced by a more complex disaggregated model. (This is a primary

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[3]A fuller discussion of sampling statistics is contained in Larson (1969), pp. 195-216.

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motivation for using an extensive-tree analysis or Step-Through rather than a simple model.) Thus, increasing the number of steps in Step-Through can frequently offer a reduction in modeling error without affecting sampling error.

2.0   ILLUSTRATIVE APPLICATION OF STEP-THROUGH SIMULATION

The best way to explain the details of the Step-Through
simulation technique is through an illustrative comparison of
the technique with an extensive-tree model in an actual
decision situation. The following sections present such a
comparison in the setting of a Navy task force commander's
decision problem, where he must decide whether to make a pre-
emptive strike against an enemy airfield. First, the problem
situation is described in some detail. Next, an extensive-
tree model of the situation is presented and, finally, a
Step-Through model of the same situation is explained.

The particular decision setting used in this illustration
is based upon the one in which the Step-Through technique was
first developed. While the initial application did not make
full use of the power of the Step-Through technique, it did
tentatively establish the feasibility of Step-Through simula-
tion and point the way for its subsequent development and
refinement.

2.1   Setting for a Pre-emptive Strike Decision

The following sections describe a realistic, but hypo-
thetical, decision situation that might be faced by a U.S.
Navy task force commander, designated as CTF Delta, who is
operating under an air strike mission directive.[1]

2.1.1   Events leading to a decision - Orange and Purple
are two traditionally mutually hostile minor powers who have
agreed to, and lived for some time with, a peace agreement

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[1]This scenario was written in support of the Office of Naval
Research's Operational Decision Aids project and originally
appeared in Brown, Hoblitzell et al. (1974), pp. 30-32.

that involves withdrawal by Orange from neutral territory previously occupied by her and a token presence in this area by Purple. Purple, with the support of Black, a major power, has gradually built up a force in this area and is now capable of launching a major attack against Orange, whom the U.S. supports.

Black has increased its naval operations in and near the coastal waters off Purple. Black forces in the area consist of one surface-to-surface anti-ship missile (SSM) group and two anti-submarine warfare (ASW) groups operating several hundred miles apart. In addition, Black surveillance/ intelligence vessels are known to be in the general area.

Task Force Delta, a carrier strike force of the U.S. fleet in the area, has been ordered to proceed from its present location to an objective area off the coast of Purple and to be prepared to provide support to Orange by interdicting pre-selected threat air fields and other targets in Purple. The Task Force is to proceed under full readiness conditions to avoid a confrontation with Black's naval forces, and to adopt a "wait-and-see" defensive policy until and unless it is threatened.

At the start of the scenario (T+0 hours), the strike authorization against the specified targets in Purple has not been received by the Commander, Task Force Delta (CTF Delta). Preliminary information regarding the possible strike mission against Purple has been received, and CTF Delta is preparing the mission plan. Initial estimates indicate that three days of strike operations will be required to accomplish the mission objectives.

The Task Force is composed of two carrier task groups: TG Delta One, which is proceeding east to the

objective area and has been designated as the strike group; and TG Delta Two, which is proceeding south to rendezvous with TG Delta One at T+24 (hours) and has been designated the escort and force defense group.

Enroute to the rendezvous with TG Delta Two, one of Black's ASW groups is reported operating south of TG Delta One on an eastern course, and the Black's SSM group is reported east of TG Delta One on a northerly course. ASW A/C from the two task groups have reported contacts with two of Black's conventional submarines, but no contacts with Black's SSGN known to be operating with the Black's naval forces have been reported.

At T+24 the rendezvous is completed, and CTF Delta has received authorization for the strike mission against Purple. The Task Force is proceeding at high speed in order to arrive at the objective area and begin mission strikes at T+40. Black's SSM force has changed course and is pursuing the Task Force at high speed.

In addition to the anti-ship missile threat to the Task Force from Black's surface and sub-surface units, Black and Purple have 27 medium-range bombers and 20 long-range bombers at fields west of the objective area. Those aircraft constitute an air-to-surface missile threat as well as a conventional bombing threat to the U.S. task force. Planning information given to CTF Delta indicates a high probability of Black's intervention, ranging from harassment of the Task Force to a limited local naval engagement.

2.1.2 The decision and its possible consequences - The decision facing CTF Delta is whether to make an early strike, at time T+36, on the three bomber bases closest to the proposed operating area, rather than to strike later as planned,

and if so, which of two defensive postures to adopt. The motivation of the early strike is primarily to reduce the potential air threat to the Task Force. However, this action has the disadvantage of reducing the surprise element in the attacks on the primary mission targets and could result in an earlier reaction by Purple, Black, or both.

The Commander is uncertain about the degree of hostile reaction to either this early strike or the planned mission strikes and the timing of that reaction. While he must be prepared to defend the Task Force against all possible levels of attack, he must carry out his primary mission in spite of any attacks on his forces and any resulting damage and losses which may occur. He must also be concerned that his initial and subsequent decisions remain within the constraints (rules of engagement) imposed by higher authority so that his actions do not unnecessarily precipitate a local naval war involving third parties. These considerations define the value dimensions for the outcomes of his decision: avoiding an engagement with Black, minimizing loss and damage sustained by the forces, and achieving success in accomplishing the primary mission.

Once into the execution phase of the mission, the Commander may be confronted with numerous decisions as the tactical situation evolves. Typical of these are:

o   Make a pre-emptive strike against Black's SSM forces at the first indications of their reaction to either the early strike on bomber bases or the planned mission strikes, as opposed to the "defend-if-attacked" posture;

o   In the event of an enemy reaction, continue mission air strike operations while defending the force, or

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concentrate all assets on task force defense and on
attacking the enemy forces and resume mission
strikes only after the threat has been reduced or
eliminated; or

o   Change the force disposition during an engagement
as the threat and assets available to counter it
change (and protection of damaged assets is indi-
cated) or wait until the engagement is over to
initiate SAR and salvage operations and reorgani-
zation of remaining force assets.

When the dust has settled on the incident, the
main overall consequences by which the initial early strike
decision will be regretted or upheld are: whether superpower
Black has been drawn into the conflict, damage to U.S.
forces and success of the mission.

2.2 Extensive-Tree Analysis of a Decision

As explained in Section 1.2 above, the Step-Through
simulation procedure does not require the specification of a
complete explicit extensive-tree model of the decision
problem. However, in order to highlight the similarities and
differences between the Step-Through and the extensive-tree
techniques, an analysis of this decision situation will be
presented first in the form of an extensive-tree model.
Subsequently, in Section 2.3 below, the Step-Through procedure
will be applied to the same decision problem.

In principle, it is possible to draw a very extensive
tree of this decision situation, a very detailed description
of all possible sequences of events and subsequent actions
following each of the task force commander's (CTF Delta's)
initial options. However, because such a tree would be too

complex to draw in detail, it is represented in schematic
form in Figure 2-1 (the branch definitions are given in
Figure 2-2). Unless otherwise indicated by a dotted line,
each branch of a node is followed by the next complete node,
with the result that there are over a million paths through
the complete tree. To complete an extensive-form analysis of
this tree, it would be necessary to assess conditional
probabilities at all of the event nodes encountered along
each path, evaluate the attractiveness of each endpoint, and
calculate an expected value for each option. Clearly, this
is an unmanageable task, and it has not been done for this
illustration.

However, the attractiveness or value of the endpoints
was adequately captured by the outcome of three contributing
events: U.S./Black engagement, engagement damage, and
mission success.[2] Since there are a small number of combina-
tions of these events and since their valuation is also used
in the Step-Through model, this evaluation was performed, as
presented in Figure 2-3. This figure shows the relative
attractiveness of each possible outcome. The most preferable
outcome, assigned a value of 100, is "complete mission
success without an engagement with Black." The least pre-
ferred outcome, assigned a value of 0, is "U.S./Black engage-
ment resulting in heavy damage to U.S. forces and an aborted
mission." All other outcomes are of intermediate attractive-
ness and are assigned values between 0 and 100, as shown.

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[2]It can thus be considered as an example of a "staged tree"
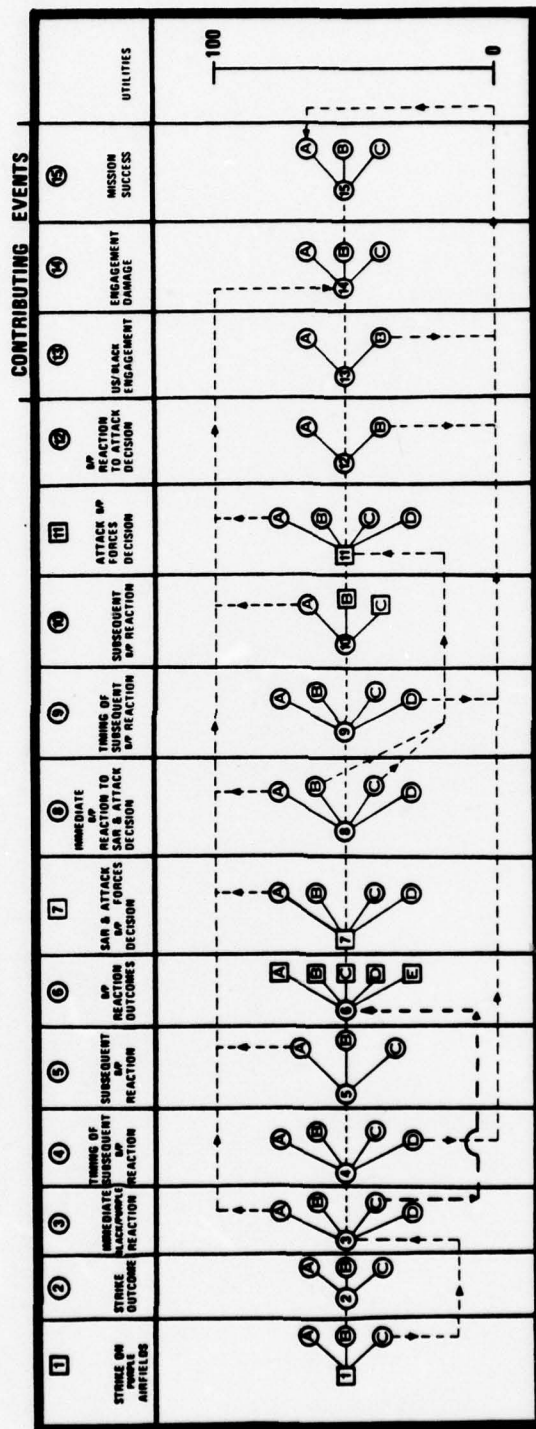referred to on page 3.

Figure 2-1
EXTENSIVE TREE

POINT	BRANCH	LABEL
1	A	Pre-emptive strike (Purple Airbases) — normal T.F. defense posture
	B	Pre-emptive strike — Increased T.F. defense posture
	C	No pre-emptive strike — normal T.F. defense posture (proceed to launch point for strike @ T+40)
2	A	Complete neutralization
	B	Partial neutralization
	C	Minimal or no damage
3	A	Black—Purple attack on task force
	B	Purple attack on task force
	C	Purple attack on Picket DD's
	D	No immediate military reaction
4	A	Military reaction occurs on 3rd day
	B	Military reaction occurs on 2nd day
	C	Military reaction occurs late in first day (T+50)
	D	No military reaction
5	A	Black — Purple attack on task force
	B	Purple attack on task force
	C	Purple attack on Picket DD's
6	A	2 DD's sunk/out of action
	B	1 DD sunk/out of action; 1 damaged/still operable
	C	2 DD's damaged/still operable
	D	1 DD damaged/still operable
	E	No/minimum damage
7	A	Immediate SAR and replacement operations
	B	No immediate SAR or replacement operation
	C	Attack Purple patrol boat base
	D	No attack
8	A	Black — Purple attack on task force
	B	Purple attack on task force
	C	Purple attack on SAR/replacement OPS and DD's
	D	No further Black—Purple attack
9	A	Military reaction occurs on 3rd day
	B	Military reaction occurs on 2nd day
	C	Military reaction occurs late in first day (T+50)
	D	No military reaction
10	A	Black-Purple attack on task force
	B	Purple attack on task force
	C	Purple attack on picket replacements
11	A	Attack black missile ship force
	B	Attack "F" class and OSA base
	C	Attack patrol boat base
	D	No attack
12	A	Black attack on task force
	B	No further black — purple attack
13	A	U.S./Black engagement
	B	No U.S./Black engagement
14	A	Heavy damage to U.S. task force, light damage to Black Forces
	B	Moderate damage to both U.S. and Black forces
	C	Light damage to U.S. task force, Heavy damage to Black for
15	A	Complete success
	B	Partial success
	C	Mission aborted

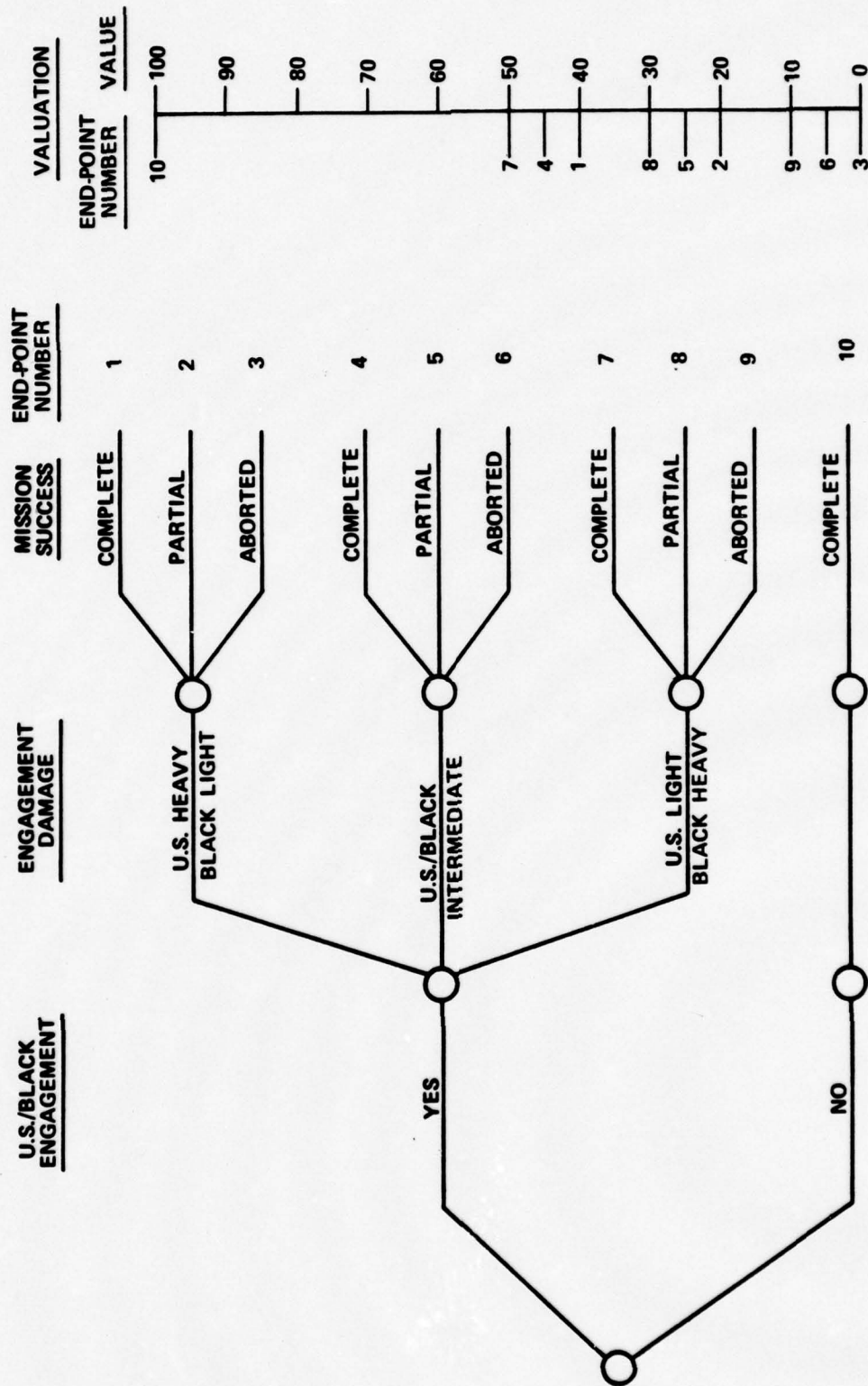## Figure 2-2

BRANCH DEFINITIONS FOR FIGURE 2-1

Figure 2-3

VALUATION OF CONTRIBUTING EVENTS

2.3 Step-Through Analysis of a Decision

The discussion below illustrates the use of Step-Through simulation to model CTF Delta's decision problem described above. As an aid to the reader, the correspondence between the Step-Through and the extensive tree analyses will be shown in some of the figures of this section. The accompanying discussions, however, will describe the Step-Through procedure as it would be carried out, without first providing a description of the underlying tree structure. The underlying structure is not provided first because Step-Through is used as an aid in structuring as well as evaluating a decision problem. Indeed, Step-Through may be used to set the stage for a subsequent extensive-tree analysis, not necessarily at the same level of detail.

Assume that prior to the beginning of the first Step-Through sequence, the outcome values for combinations of contributing events have been assessed, as given previously in Figure 2-3. The decision maker may now begin to evaluate his initial options by using Step-Through sequences. For instance, the decision maker may first wish to evaluate the alternative, "No preemptive strike (proceed to launch point for strike at T+40)."

If the decision maker selects this alternative to evaluate, he would then specify what events might follow such an action. As shown in Figure 2-4 (the simulation sequence is shown as a bold path in the extensive-tree diagram), he specified that Black or Purple might react with an attack against the U.S. task force. The decision maker or some other expert would then supply a probability distribution over the possible Black or Purple responses. Based on the assessed probability distribution, a result for
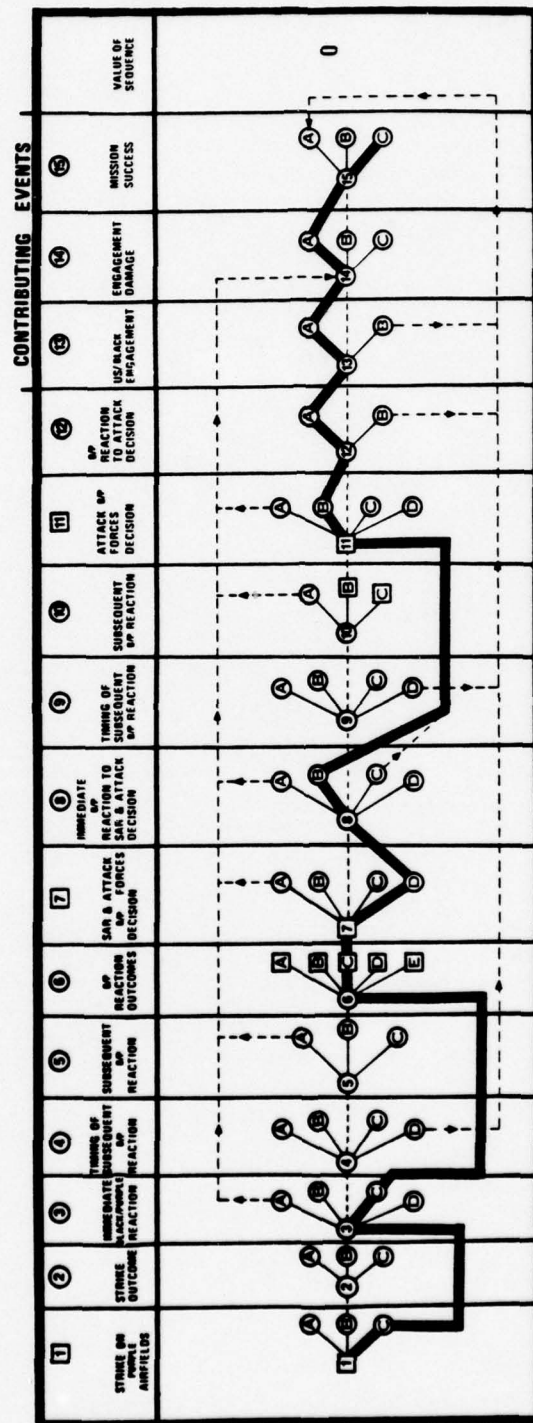
Figure 2-4

STEP-THROUGH SIMULATION SEQUENCE I

this node is simulated by using the Monte Carlo procedure.[3]
In the illustrative sequence shown, the simulated result at
this node is "Purple attacks U.S. picket ships." Next, the
decision maker would describe the next act or event of
importance, which, as shown in Figure 2-4, is the outcome of
the Purple attack. This event node is then defined by
indicating the possible results and their probabilities, and
the Monte Carlo procedure would again simulate the result,
in this case, that "two destroyers are damaged but still
operable." Next, the decision maker would indicate that a
decision is required on whether or not to engage in either
replacement operations or an attack against Purple. Given
the simulated situation, the decision maker might indicate
that he would not engage in either replacement or attack
actions. Note that this feature of Step-Through, that is, the
decision maker chooses subsequent actions as they are en-
countered, is different from conventional Monte Carlo
simulation in which subsequent actions are specified according
to a decision rule. (However, it could have been treated
the same if the choice were between complete strategies,
rather than between initial options, or if the subsequent
acts were treated as uncertain events.[4])

The Step-Through procedure continues in a similar
manner, with the decision maker choosing subsequent acts and
simulation determining the results of uncertain events,
until the outcome is determined, in this case in terms of
the contributing events and their values. The outcome of the
first sequence, is shown in Figure 2-4: A U.S./Black engage-
ment resulted in heavy damage to the U.S. and caused the

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[3]An introductory-level description of the Monte Carlo procedure
is presented in Schlaifer (1969), ch. 13.

[4]See Brown, 1975.

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mission to be aborted. As indicated in Figure 2-4, this outcome is the worst possible, with a value of 0. Thus, the first trial path drawn for the action, "No pre-emptive strike, proceed to launch point for strike at T+40," has a value of 0. This single trial, however, yields very little information about this action. To gain useful information about the action, a representative sample of several trial paths through the tree must be drawn by repeating the process described above. Such a sample will result in a frequency distribution of value for the action such as that shown in Figure 2-5 for 20 sample paths beginning with the "No pre-emptive strike" action.

This frequency distribution can then be compared with frequency distributions obtained from Step-Through samples for the other actions to determine the preferable option. For example, Figure 2-6 shows possible frequency distributions that might be obtained by sampling 20 paths for each action. Such samples can be used as a basis for a decision. In this illustration, for instance, the action "Pre-emptive strike with increased defense" might be preferable because it has a much higher estimated mean and only a slightly higher estimated standard deviation than "No pre-emptive strike."[5] On the other hand, "Pre-emptive strike with normal defense" might be the least preferable alternative since it has both the lowest estimated mean and the highest estimated standard deviation.

In general, the length of the trial path and consequently the number of elicitations required in the trial

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[5] The estimates in Figure 2-7 are the maximum likelihood estimate of the population mean and standard deviation for a normally distributed population. See Larson (1969), ch. 7, for a discussion of statistical estimation and the maximum likelihood method.
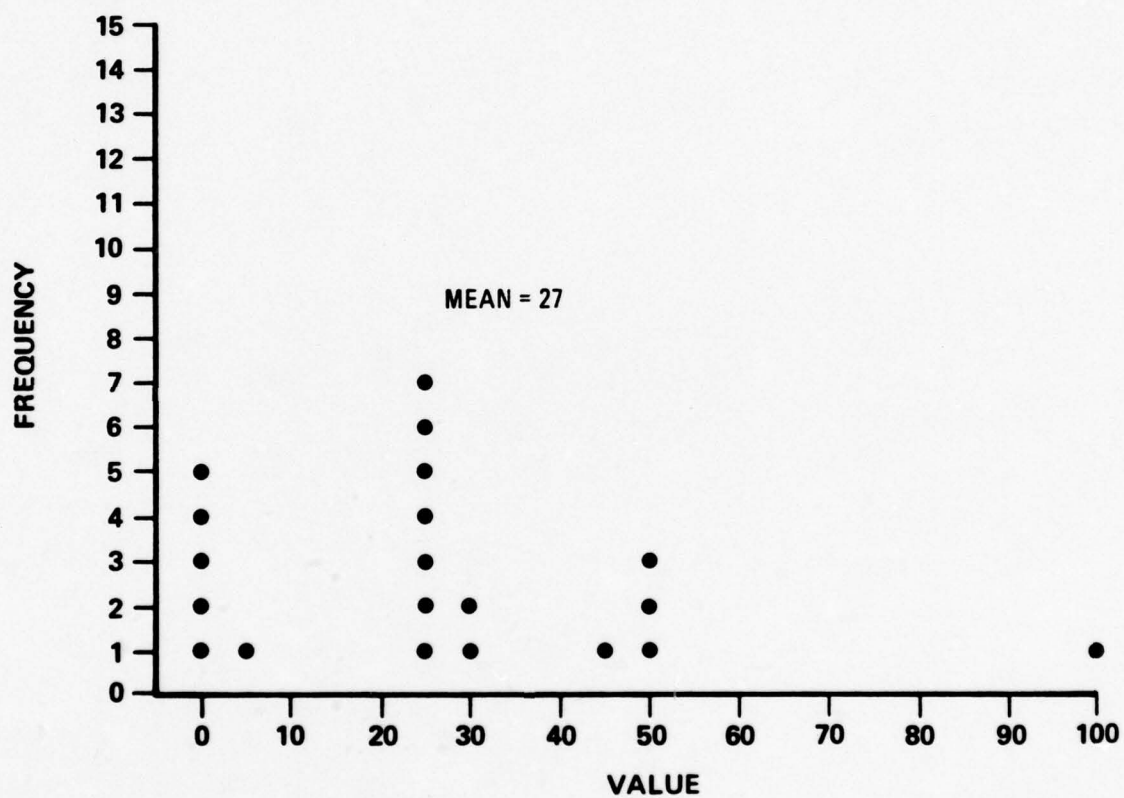
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Figure 2-5

ILLUSTRATIVE SAMPLE OF VALUES FOR "NO PRE-EMPTIVE STRIKE"
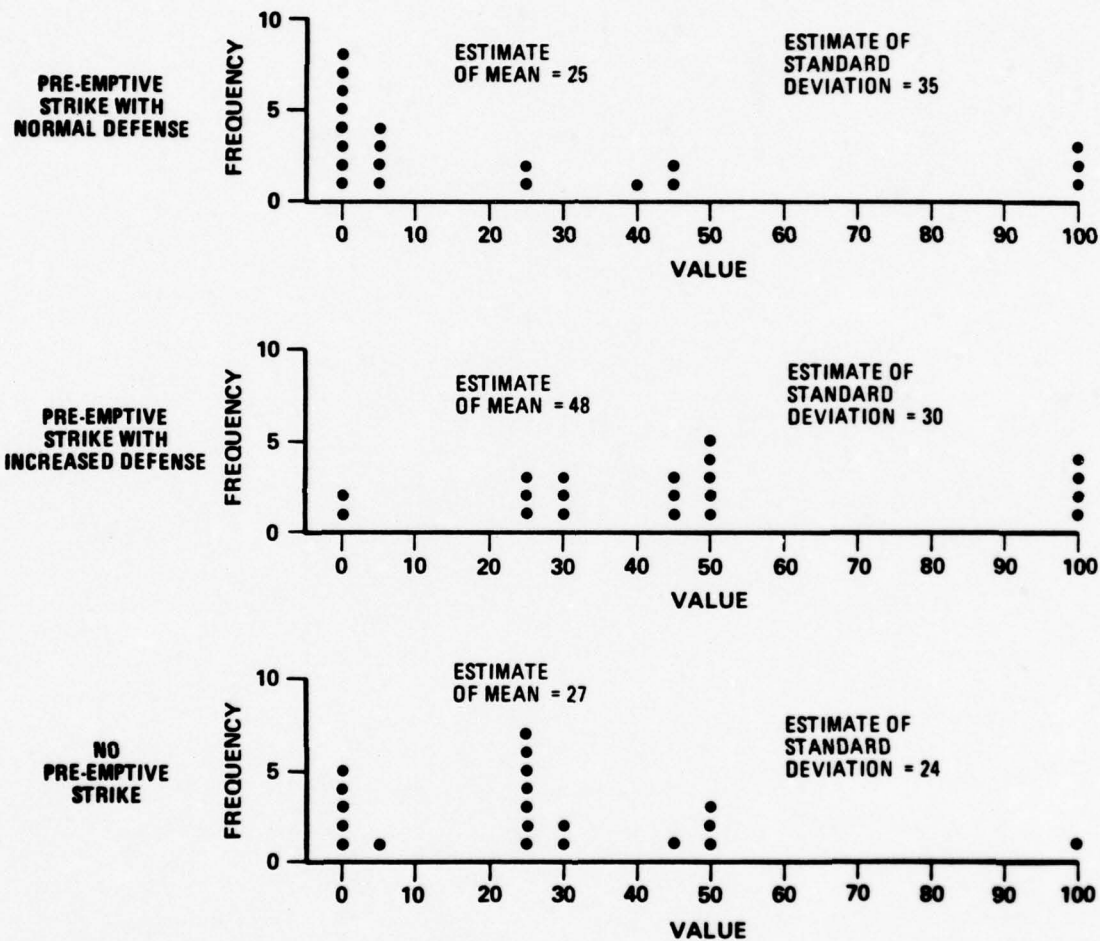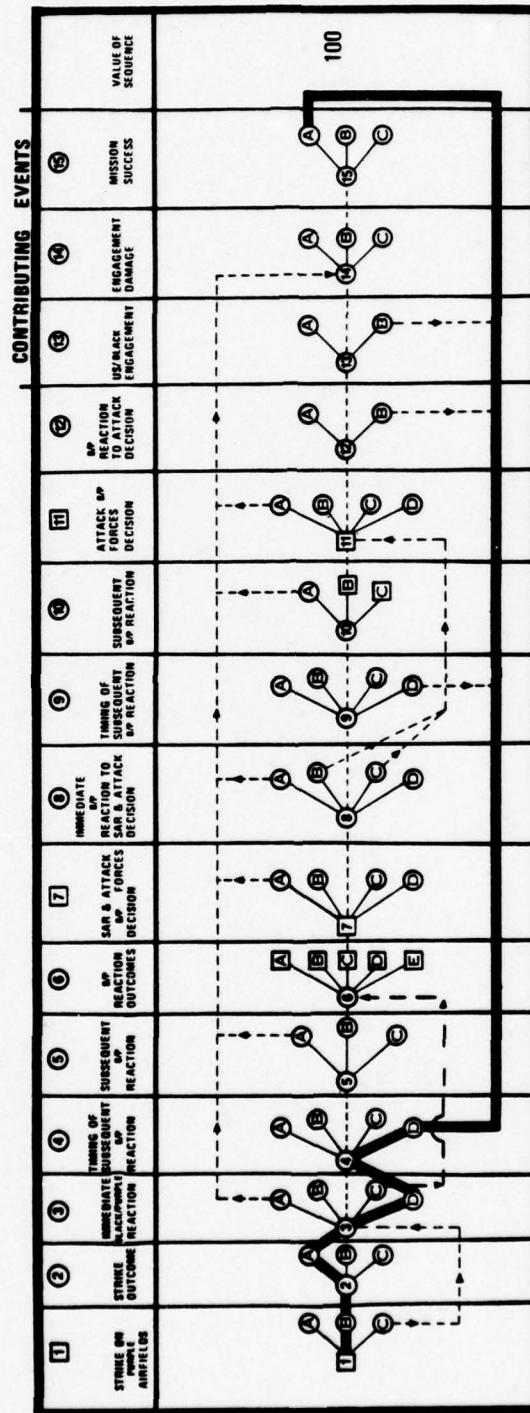
Figure 2-6

ILLUSTRATIVE SAMPLES OF VALUES FOR ALL ACTION ALTERNATIVES

will vary from trial to trial. Figure 2-7 shows a trial
path that is much shorter than the one illustrated in Figure
2-6.

Figure 2-7

STEP-THROUGH SIMULATION SEQUENCE II

3.0   TESTING THE USEFULNESS OF STEP-THROUGH

Experience in developing the Step-Through variant promised
to be useful in a variety of real decision situations where
a complex decision model is required. However, some testing
activity was needed to confirm this hypothesis. Specifically,
the testing activity described below was undertaken to
establish a preliminary determination of the elicitation and
computational advantage if any of Step-Through over a complex
extensive-tree analysis, to gain insights into the technique
of implementing Step-Through, and to identify the strengths
and weaknesses of the computer prototype (see Appendix A) in
order to suggest software refinements.

3.1   Testing Approach

Since Step-Through is a new technological idea, it is
probably most fruitfully tested by workshop trials, that is,
informal reflections based upon trial applications of the
methodology in an opportunistic sample of decision situations.
This method of testing is not as complex or as rigorous as a
controlled experiment and consequently does not produce results
that are as definitive. However, at this early stage of
development, useful insights can be obtained most economically
through workshop trials. If the results of this testing
activity indicate that Step-Through is a viable procedure,
more controlled experimentation may be indicated for a later
time.[1]

Five workshop trials using a variety of decision problems
and decision makers were conducted. Problems included

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[1]The interested reader can find a more complete discussion of
the range of possible evaluation techniques and the reasons
for choosing each in Brown and Watson (forthcoming).

military decisions of the type presented in Section 2.0 and
personal career decisions. Subjects included trained decision
analysts and military officers both with and without exposure
to decision analysis techniques. The trials were carried
out after various amounts of pre-modeling effort (structuring
the sequence of acts and events, assigning values, and
assessing probabilities). At one extreme, Step-Through was
used as a first formal consideration of the problem, without
any pre-modeling. At the other extreme, Step-Through was
used to evaluate and refine a decision model that had
already been substantially, although not completely, modeled.
This pre-modeling included an elicitation of the complete
schematic sequence of acts and events, an elicitation of an
influence diagram describing the conditional nature of the
probabilities, and an assignment of outcome values. At an
intermediate level of pre-modeling, Step-Through was used
after eliciting a modal path through the tree for each
initial option, identifying the value criteria, and assigning
values to outcomes.

3.2 Test Results

As mentioned above, test results were primarily sought
to determine the elicitation and computational advantage, if
any, of Step-Through over an extensive tree, to gain insights
into the proper implementation techniques for Step-Through,
and to identify necessary software refinements. These results
were sought in order to establish conclusions on the viability
of the Step-Through variant of decision analysis, the proper
method of its application, and the proper direction for its
future development.

The pilot testing results supported our initial assump-
tion that Step-Through can offer a considerable economy of
elicitation and computation effort over a complex extensive

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tree. The amount of advantage offered by Step-Through,
however, was found to depend critically upon the proper
implementation of the method, especially with respect to the
proper amount of pre-modeling. That is, both too little and
too much pre-modeling of a decision problem was found to
affect adversely the advantage of Step-Through. When used
with little or no pre-modeling, it produced models that were
grossly inaccurate simplifications of the decision situation.
On the other hand, a high degree of pre-modeling produced
structurally sound models, but the pre-modeling itself
required a large elicitation effort and thus reduced the
advantage of Step-Through. When a moderate amount of pre-
modeling was performed, however, a structurally sound model
was obtained at a modest elicitation cost. Overall, when
properly implemented, Step-Through was found to reduce the
total elicitation and computational burden of an extensive-
tree analysis of comparable complexity by over 50%. This
advantage can be expected for moderately to highly complex
decision models, that is, those containing ten or more tiers
of nodes.

The workshop trials proved to be very useful in answering
four implementation questions:

1. Should other forms of decision analysis be attempted
    before applying Step-Through?

2. How much does the decision maker need to be involved
    in a Step-Through modeling effort?

3. How much does a decision analyst need to be involved
    in a Step-Through modeling effort? and

4. How much pre-modeling should precede the Step-
    Through procedure?

The tests indicate that the Step-Through procedure is most effective when it is used after a moderate amount of pre-modeling. The pre-modeling should consist of an elicitation of a modal or most likely path through the tree for each immediate action alternative, an elicitation of the criteria of value in the decision situation, and an assignment of values to the possible contributing events. As mentioned above, Step-Through offers its greatest economy of elicitation and computation when a moderate amount of pre-modeling is performed. Further, our tests indicate that moderate pre-modeling helps to reduce the amount of confusion that the decision maker experiences during the Step-Through procedure, and this enables him to provide inputs that accurately reflect his perceptions of the decision situation.

The tests indicate that Step-Through should not be used as the first formal method of analyzing a decision problem. Step-Through was found to require a large commitment of resources in terms of monetary expense, a decision analyst's time, and the decision maker's time. Consequently, a Step-Through analysis can be justified only in decision situations that cannot be adequately addressed by less costly analytic techniques, such as a direct probability model.[2] Thus, it is prudent to attempt a less costly analysis before attempting to apply Step-Through, unless Step-Through with very few trials, or in its less expensive modal form, is used to prepare the way for another approach by sensitizing the subject's judgment.

The workshop trials indicate that the decision maker needs to be heavily involved. His heavy involvement increases

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[2] For a discussion of how alternative decision analytic approaches compare on cost, precision and other measures of performance, see Brown and Ulvila (1976).

the chances that an accurate model will result and that the decision maker will understand the output of the model. With heavy involvement of the decision maker, Step-Through effectively highlights the key considerations of a decision problem in a way that facilitates their precise modeling and estimation. This results in an accurate model of the decision problem. Heavy involvement is also necessary to communicate the results of the model, that is, the probable consequences of selecting each initial option. In addition, the tests indicate that heavy involvement of the decision maker in Step-Through analysis serves an immediate training function by increasing his understanding of the decision situation. On the other hand, without heavy involvement of the decision maker, it is extremely difficult, if not impossible, to obtain a Step-Through model that accurately reflects the decision maker's perception of his problem. Moreover, it is very difficult to communicate the output of the model to the decision maker.

The workshop trials indicate that a decision analyst also needs to be heavily involved in the Step-Through modeling procedure to guide the decision maker through the sample paths and to provide an interpretation and explanation of the output. Otherwise, there is a high probability that a poor model and an inaccurate interpretation of its output will result.

With regard to the computerized version of Step-Through described in Appendix A, the workshop trials indicate that substantial modifications are necessary to bring the program to a final product stage. Most importantly, modifications must be made to streamline the operation and interaction of the program with the user. In Step-Through models that utilized the computer program, the structure of the model was often influenced by the requirements of the program.

This influence was in the direction of pressuring the user to define shorter paths and less complicated forks.

These are clearly undesirable features of the computer program; however, we feel that they can be overcome by modifying the software.

The current program strains the user's memory capacity by requiring him to remember the details of each trial path, including the sequence of acts and events modeled and the previous assessments of utilities and probabilities. The user can alleviate the strain by defining short paths in the model. Alternatively, a computer modification could relieve the strain by providing the user with a summary description of the path and by allowing him to backtrack in the path. The pressure to define simple forks is caused by the laborious procedure that is required by the program for fork definition. This pressure can be removed by a modification that stream-lines the interactions necessary to define the forks.

The modifications mentioned above are intended to correct shortcomings in the program. Furthermore, the program would be more useful if it provided additional output, for example, a running estimate of the mean value and a measure of dis-persion around the mean (such as the standard deviation, a central 90% credible interval, or another similar measure) in addition to the frequency distribution, separate frequency distribution displays for each immediate action alternative, and separate frequency distribution displays for each criterion of value.

4.0 CONCLUSIONS

Limited development, application, and testing allow
only tentative conclusions about the usefulness of the Step-
Through variant of Monte Carlo simulation for structuring a
decision model, pruning a decision tree, and evaluating
initial options. Because Step-Through offers elicitation
economies over the extensive-tree variant, and because it
retains the disaggregation properties of the extensive tree,
Step-Through is a very effective procedure for developing an
accurate structure of a complex decision situation. Because
the Step-Through procedure effectively identifies the key
parameters in a decision model, it is a useful procedure for
pruning an extensive decision tree by eliminating superfluous
branches. Because Step-Through offers elicitation and compu-
tational economies over an extensive tree and because Step-
Through enables an accurate structure of a decision situation,
it is a useful technique to evaluate initial options as a
basis for choice among them.

The application and testing activity also revealed that
Step-Through is a useful procedure for training decision
makers for contingent situations. In particular, its ease
of operation and limited demands, compared with conventional
Monte Carlo simulation, enable a decision maker to simulate
easily an uncertain future situation and to develop an
understanding of the situation and a "feel" for the best
response to it.

On the other hand, Step-Through does not appear to be a
promising variant to use as an initial formal approach for
modeling a decision situation, for evaluating subsequent
acts in complete decision strategies, or for use without
expert supervision. The workshop trials have shown that
Step-Through requires a large commitment of resources and

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thus is justified only after simpler modeling techniques prove to be inadequate. In addition, Step-Through appears to produce over-simplified structures of complex decision models when no previous formal modeling is performed.

Since only a small fraction of the sample paths through the implicit decision tree will contain the same setting for subsequent acts, a Step-Through analysis to evaluate complete strategies requires a sample that is too large to be practical. Since the Step-Through procedure is fairly complicated and since the output of a Step-Through model is fairly difficult to interpret, a good Step-Through analysis requires a high degree of participation from both the decision maker and a trained decision analyst.

On the basis of testing, it appears that the prototype computer implementation of Step-Through must be modified before it is suitable for a production environment. In particular, its operation must be streamlined to remove the pressure on the user to define Step-Through models containing short paths and simple forks. In addition, the computer program can be enhanced by providing the user with additional output.

Finally, the testing that has been completed suggests that the viability of the Step-Through variant warrants further testing, development, and application, both in controlled experimental settings and in applications to real decision problems.

APPENDIX A

PROTOTYPE COMPUTER SOFTWARE IMPLEMENTATION[1]

A prototype interactive computer graphic software package
has been developed to test the feasibility and usefulness of
the Step-Through variant of Monte Carlo simulation. While
a manual implementation of Step-Through is sufficient to
yield some tentative insights into its conceptual feasibility
and implementation, the manual procedure is tedious and time
consuming, especially in such areas as performing the Monte
Carlo procedure. A much more powerful realization of the
concept can be effected by using a computer. In addition,
interactive computer graphics offers a streamlined interface
between the user and the machine. Thus, the interactive
computer graphics program is expected to ease the user's
computational tasks and keep his focus on the decision
problem while the computer keeps track of the technicalities
of the Step-Through procedure.

The following sections describe the key features of the
"Step-Thru Monte Carlo Decision Analysis System" (MONTE), as
it is implemented to run on the computer installation at
Decisions and Designs, Incorporated. This installation con-
sists of a PDP-11/40 minicomputer with a Vector General DD3
graphic display system. Once MONTE has been brought to
execution, all interactions with the user occur via the

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[1]The software described here was developed under a contract
from the Rome Air Development Center, Griffiss Air Force
Base, New York.

This section of the report is adapted from Randall and Barclay
(1975) and contains descriptions of the most important
features of the prototype computer program. For a more com-
plete description of the program, including a description
of the hardware configuration and program generation, the
reader is referred to the original document.

display system. Except for unusual error conditions, all
MONTE output appears on the display monitor. The figures
contained in the following sections are the actual displays
that appear on the monitor during the program's use.

It should be noted that the prototype software docu-
mented below has evolved under research conditions and that
it has not yet been developed to the point where it is
suitable for use in a normal production environment. Although
every effort has been made to ensure that the software is
error-free, certain aspects of the software may not be as
robust as is desirable and necessary in a production pro-
gram. For example, providing the program with invalid
inputs may cause it to fail or to produce unpredictable
results.

A.1 Beginning Program Execution

When execution begins, the display contains the image
shown in Figure A-1. The user can select one of six options
displayed by pointing at it with the light pen. When an
item has been selected, it will blink. Selecting NEW allows
the user to define a new model; selecting OLD allows him to
retrieve a previously defined model. DESTROY permits the
user to purge a model from the system. To make parametric
or structural changes in an existing model, the user can
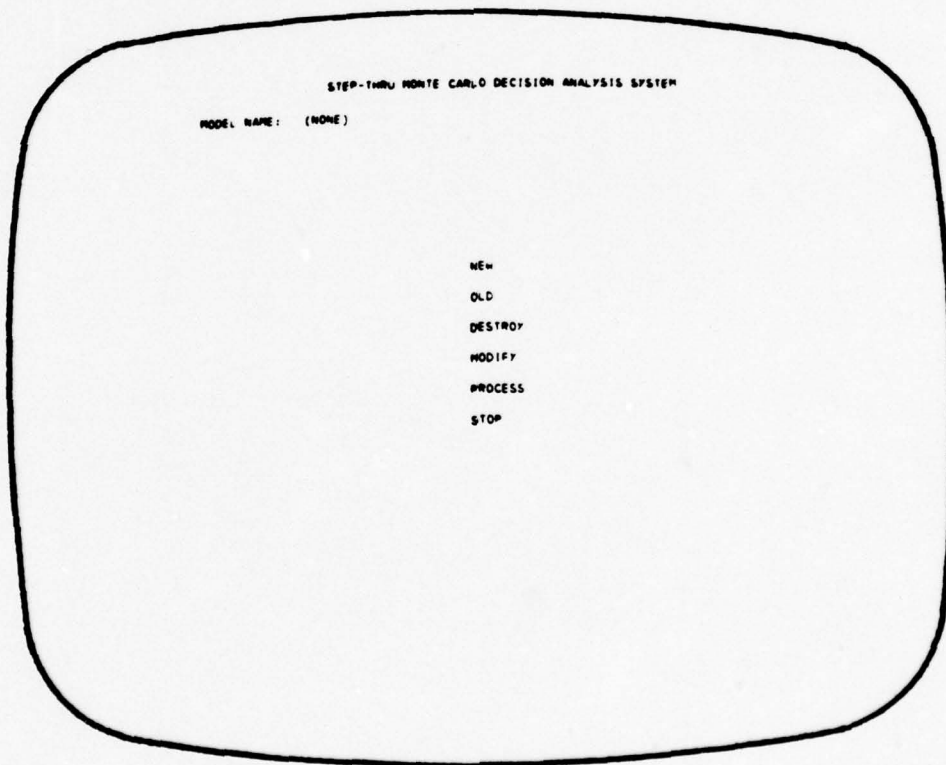select MODIFY. Selecting PROCESS initiates the Step-Through

STEP-THRU MONTE CARLO DECISION ANALYSIS SYSTEM

MODEL NAME: (NONE)

NEW
OLD
DESTROY
MODIFY
PROCESS
STOP

Figure A-1

MONITOR DISPLAY 1

procedure.   Finally, the user can terminate execution by
selecting STOP.

A.2 Model Definition

When the user selects NEW, the image of Figure A-2 appear-
ing on the screen requests the user to assign a name to the
new model. The user must enter the name via the display
keyboard and terminate the entry by depressing the carriage
return (CR) key.

STEP-THRU MONTE CARLO DECISION ANALYSIS SYSTEM

MODEL NAME: (NONE)

ASSIGN MODEL NAME:

Figure A-2
MONITOR DISPLAY 2

Once a model name, in this example, "TSTMDL," has been
specified, MONTE will display the image of Figure A-3 on the
screen. (The example model used in this section is the one
used in Randall (1975) and thus does not correspond to the

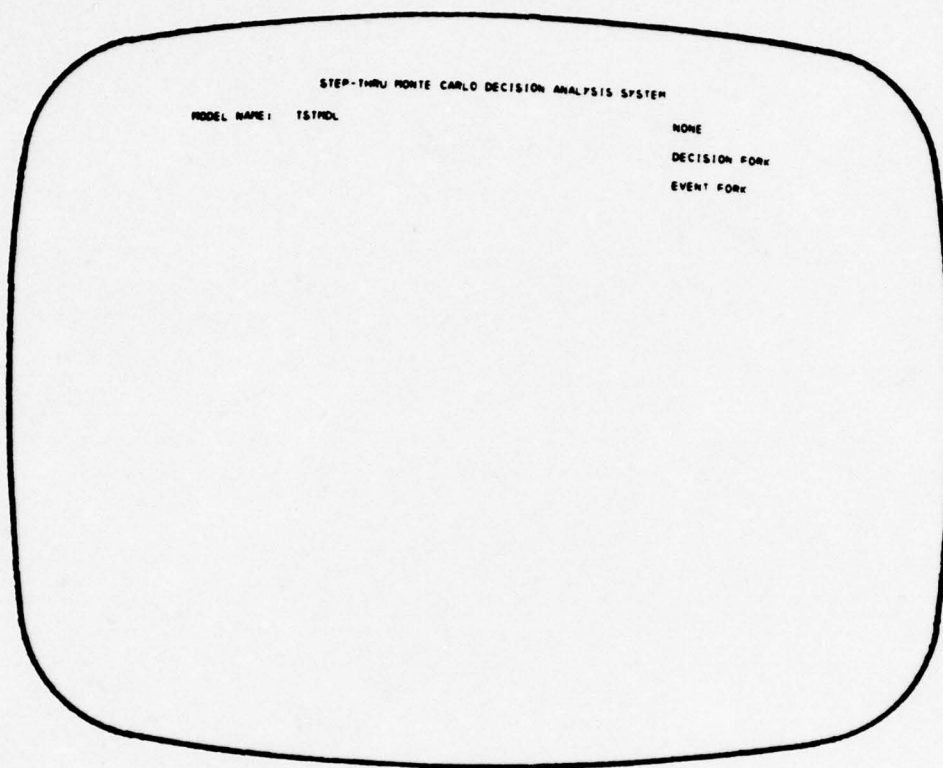illustrative application of Step-Through given in Section 2
above.)

STEP-THRU MONTE CARLO DECISION ANALYSIS SYSTEM

MODEL NAME: TSTMDL

NONE

DECISION FORK

EVENT FORK

Figure A-3

MONITOR DISPLAY 3

A.3 Fork Definition

In order to define either an event fork or an action
fork, the user must first select this item, by using the light
pen, from the list in Figure A-3. After such a selection,
MONTE will request a further description of the number of
branches emanating from the fork and a four-character I.D. for
identifying the fork, as depicted for an event fork in Figure
A-4.

Figure A-4
MONITOR DISPLAY 4

After receiving responses to these requests, MONTE will
display a fork with the number of branches and of the type
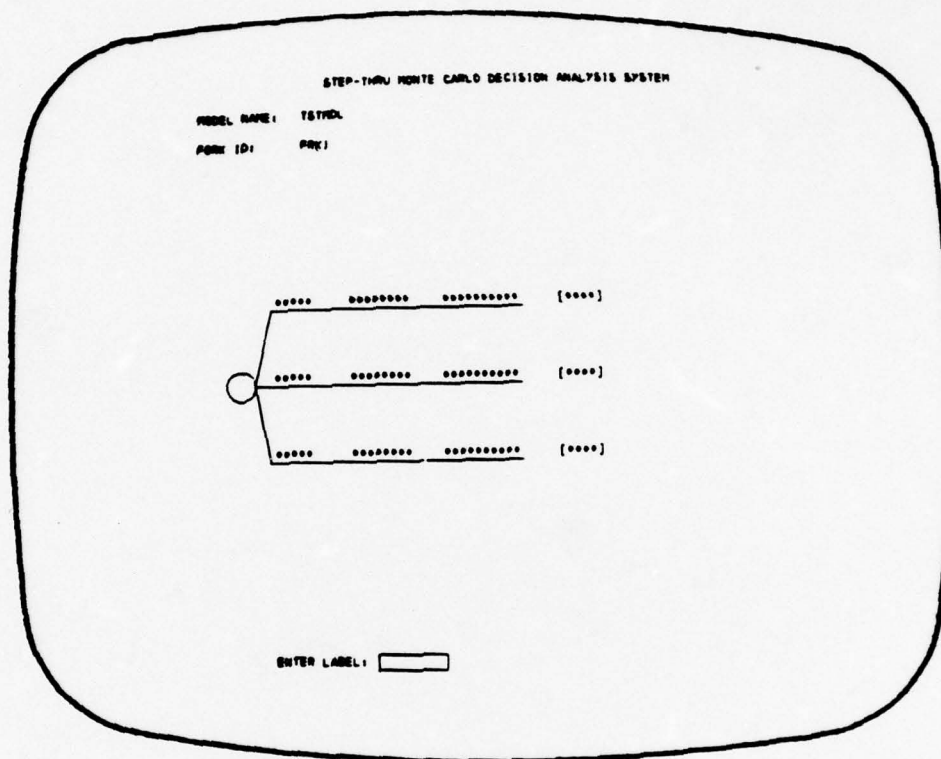
requested, as shown in Figure A-5.

STEP-THRU MONTE CARLO DECISION ANALYSIS SYSTEM

MODEL NAME: TSTMDL

FORK ID: FRK1

ENTER LABEL:

Figure A-5
MONITOR DISPLAY 5

MONTE will then allow the user to specify a value for all or
some of the parameters associated with the fork. The para-
meters of an event fork, which are shown as asterisks in
Figure A-5, are, from left to right: branch probability,
branch label, branch utility, and I.D. of the fork following
the branch (which we will subsequently reference as the
"branch link"). MONTE will cause each parameter field to
flash in turn and will request an input of the appropriate
type, as shown in Figure A-6. The user can specify branch
links in advance, or he can wait until the fork is processed

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and then specify only the link that is required as a result of
the simulation. The latter option was used in the illus-
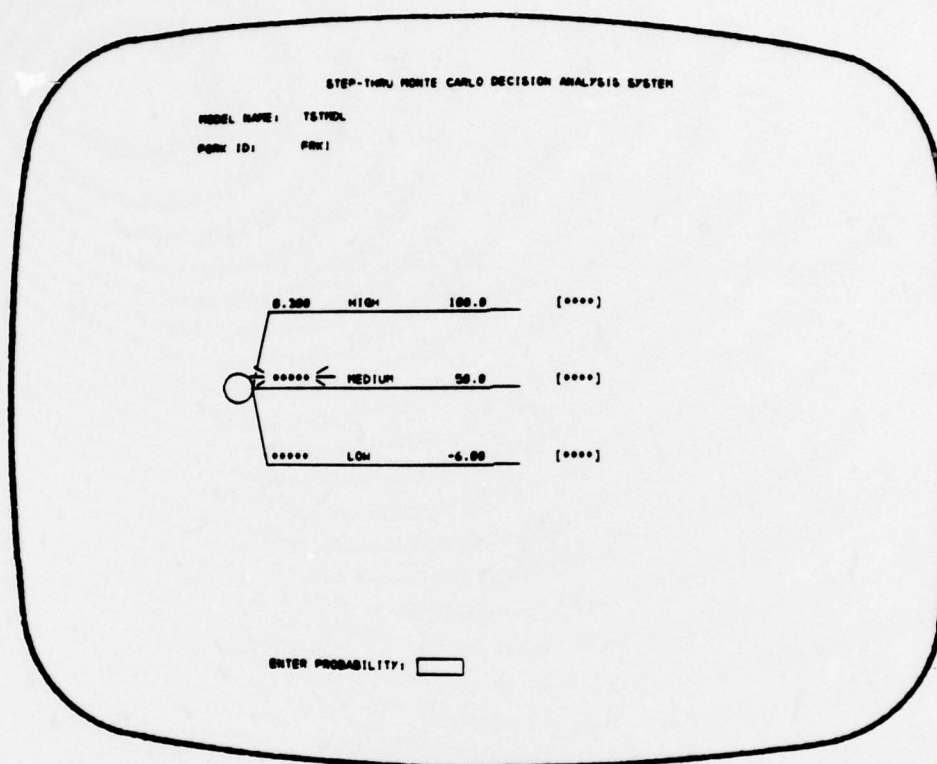tration of Section 2.2 above.

Figure A-6

MONITOR DISPLAY 6

A.4 Parameter Changes

After cycling through all parameter fields, MONTE provides
the user an opportunity to change or correct any parameter, as
in Figure A-7. He can select a parameter to be changed by
pointing at it with the light pen.

STEP-THRU MONTE CARLO DECISION ANALYSIS SYSTEM

MODEL NAME: TSTMDL   PARAMETERIZATION COMPLETE

FORM ID: FRM1

0.300   HIGH   100.0   [NOD1]

0.420   MEDIUM   50.0   [****]
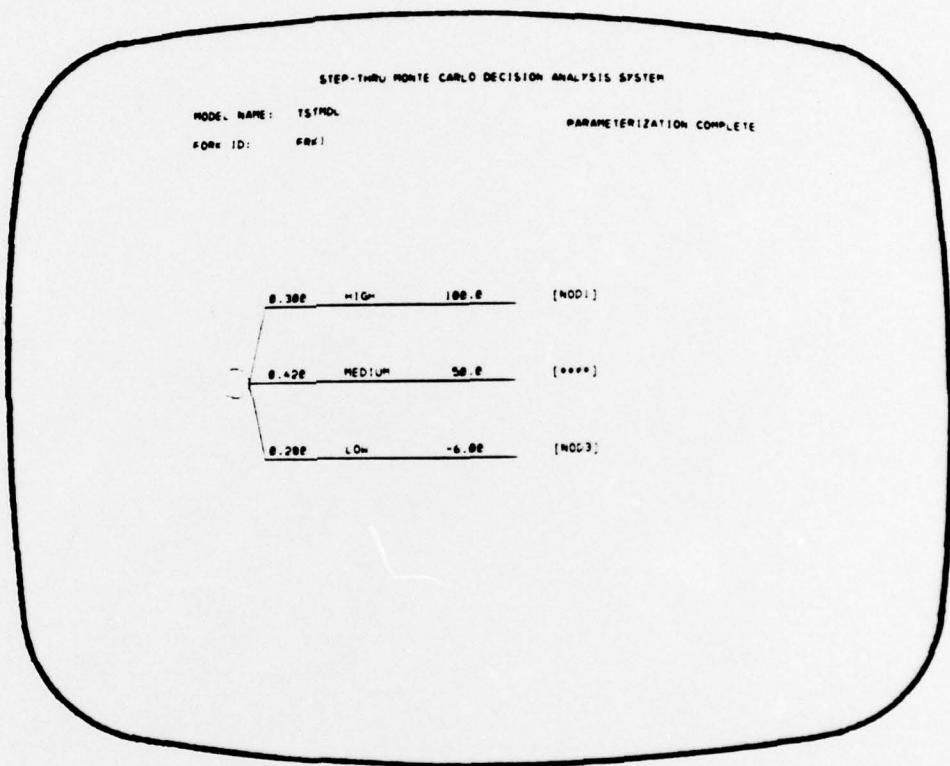
0.280   LOW   -6.00   [NOD3]

Figure A-7
MONITOR DISPLAY 7

When a parameter has been selected, it will flash, and MONTE
will request a value of the appropriate type, as in the initial
request for parameters. When all desired changes, if any, have
been made, the user can point the light pen at PARAMETERIZATION

COMPLETE in Figure A-7, and the fork definition will be complete. The image of Figure A-3 will reappear on the screen, and the user may define another fork. (A decision fork is similar in appearance to an event fork except that a square replaces the circle at the left of the fork, and the decision fork has no branch probabilities.)

When the user has defined all the forks he wishes, he may select NONE; the model definition will terminate at this point and the image of Figure A-8 will appear.
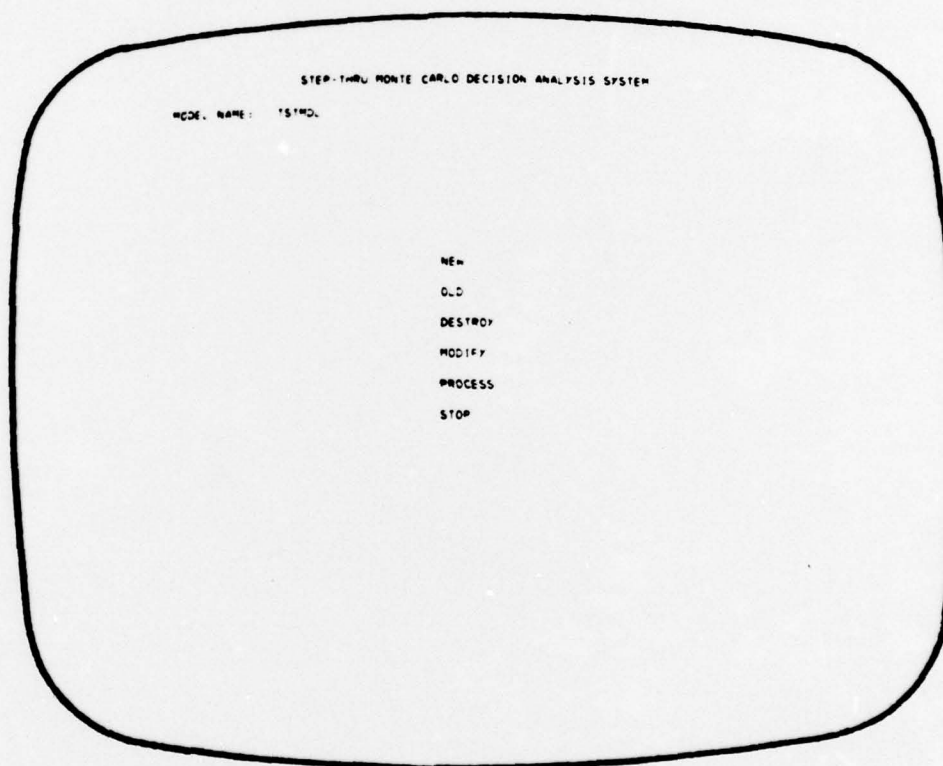

Figure A-8
MONITOR DISPLAY 8

A.5 Step-Through Processing

The user activates the Step-Through process by pointing
the light pen at PROCESS in the option list of Figure A-8.
This instruction causes MONTE to display the immediate action
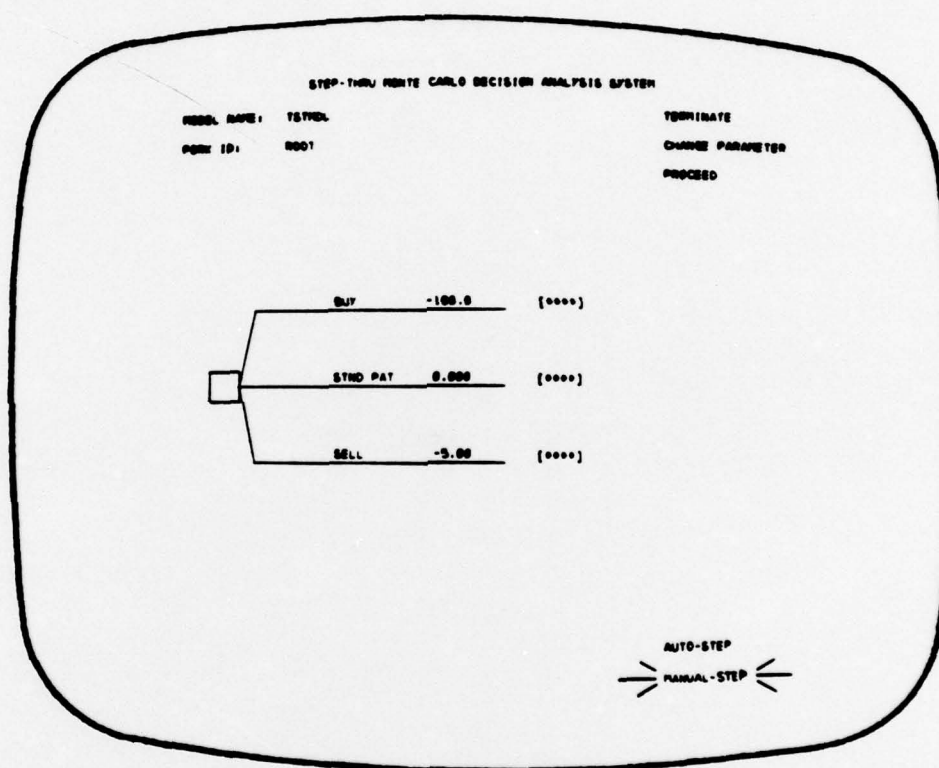choice fork on the screen, as shown in Figure A-9.

Figure A-9
MONITOR DISPLAY 9

The first step in the trial path through the decision tree is
activated by pointing at PROCEED and then at the action whose
path is to be sampled. (If the user does not wish to proceed,
he can either change the parameters of the fork or terminate
the process by pointing at the appropriate item in the option

list of Figure A-9.) MONTE then responds by causing the
branch label to flash and by informing the user that the
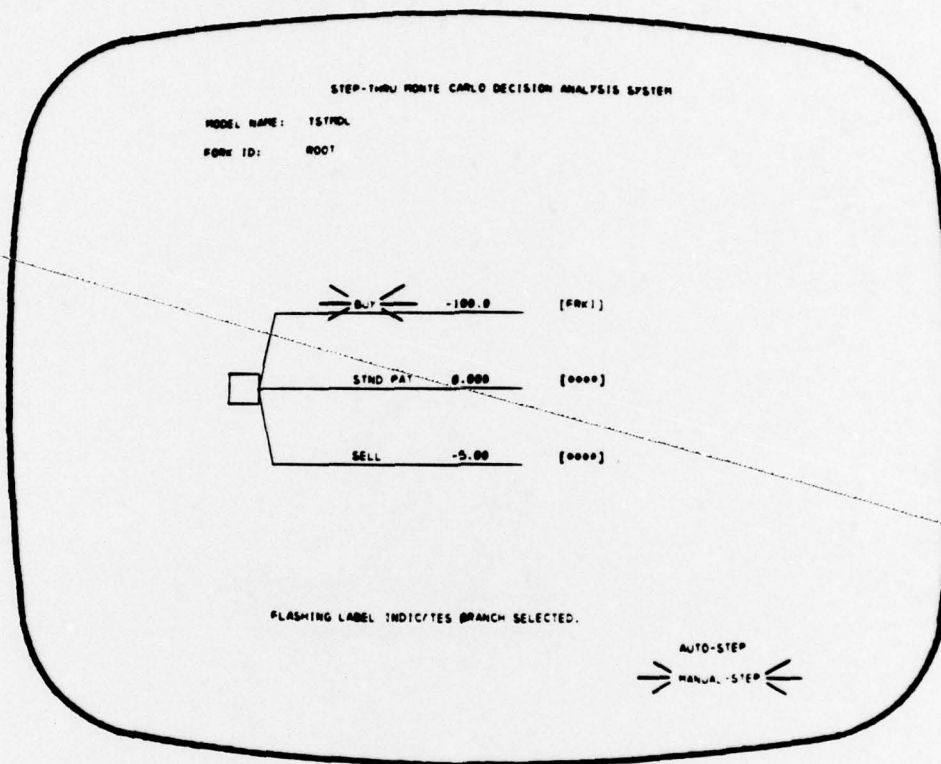corresponding branch has been chosen, as shown in Figure A-10.

Figure A-10
MONITOR DISPLAY 10

MONTE records the value of the branch utility, asks the user
to specify the branch link (in this case the branch link is
"FRK1"), and asks the user to define the next fork along the
path by using the procedure described in Section A.3 above.
The user then points at PROCEED to continue the path sample.
(Alternatively, the user can specify branch links and subse-
quent branch definitions in advance. In this case, MONTE will
automatically recall and display the next fork in the sample
path.)

If the following fork is an event fork, then MONTE uses
a random number generator to select a branch on the basis of
the probabilities assigned to the various fork branches.
MONTE then informs the user of the branch chosen, such as the
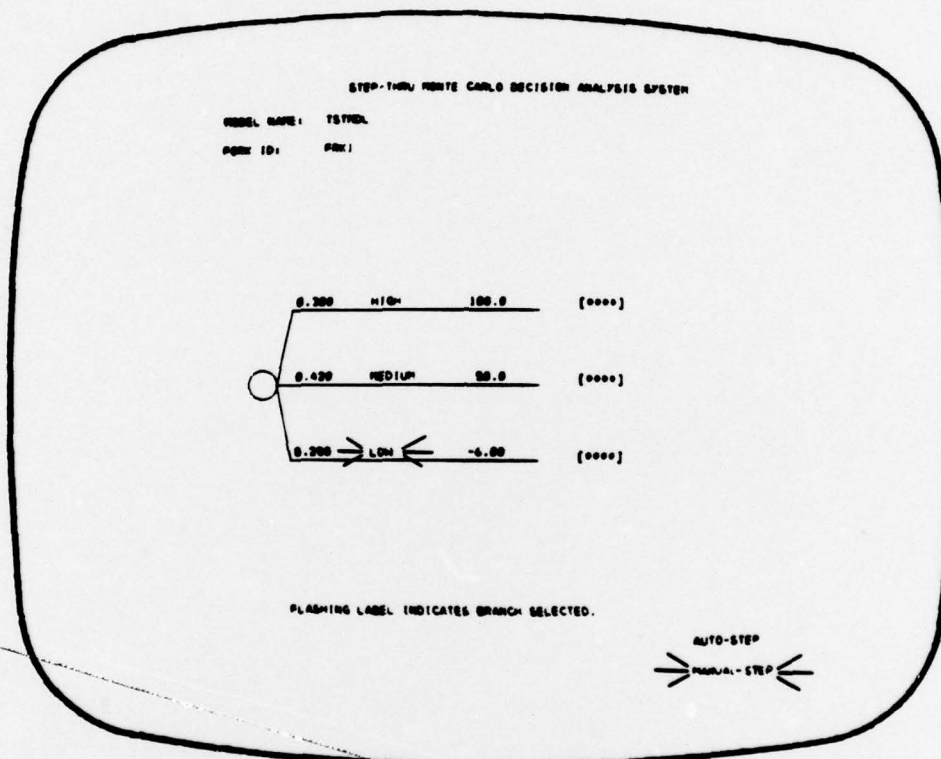choice of "LOW" shown in Figure A-11 for the event fork FRK1.

Figure A-11
MONITOR DISPLAY 11

Again, MONTE accumulates the value of the branch chosen and
asks the user to define the next fork in the sample path.

This process repeats until the user indicates the end of
the path by entering the symbol "@" as the name of the branch

link, as shown in Figure A-12. At this point, a single trial path has been completed, and the user can begin another one.

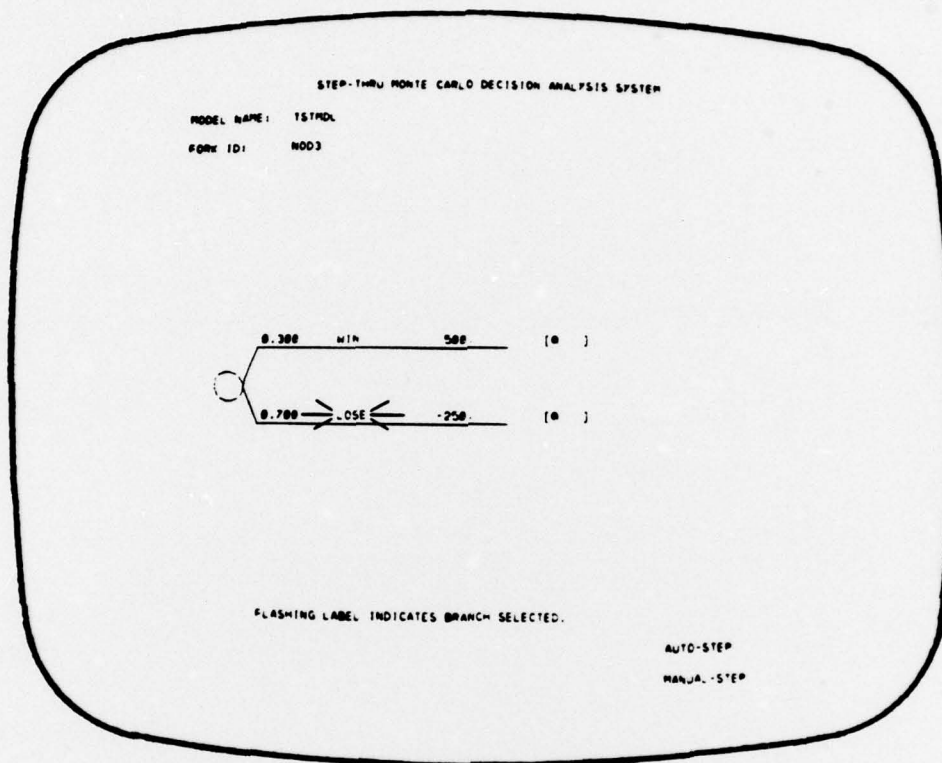

STEP-THRU MONTE CARLO DECISION ANALYSIS SYSTEM

MODEL NAME: TSTMDL

FORM ID: NOD3

0.300   WIN   500   [●]

0.700 ➞ LOSE ⬅ -250   [●]

FLASHING LABEL INDICATES BRANCH SELECTED.

AUTO-STEP

MANUAL-STEP

Figure A-12

MONITOR DISPLAY 12

A.6 Result Display

After each trial path, MONTE displays the complete sample results in the form of a frequency distribution. Figure A-13 shows such a frequency distribution for a sample of 11 trial paths. Each star on the plot represents one trial path through
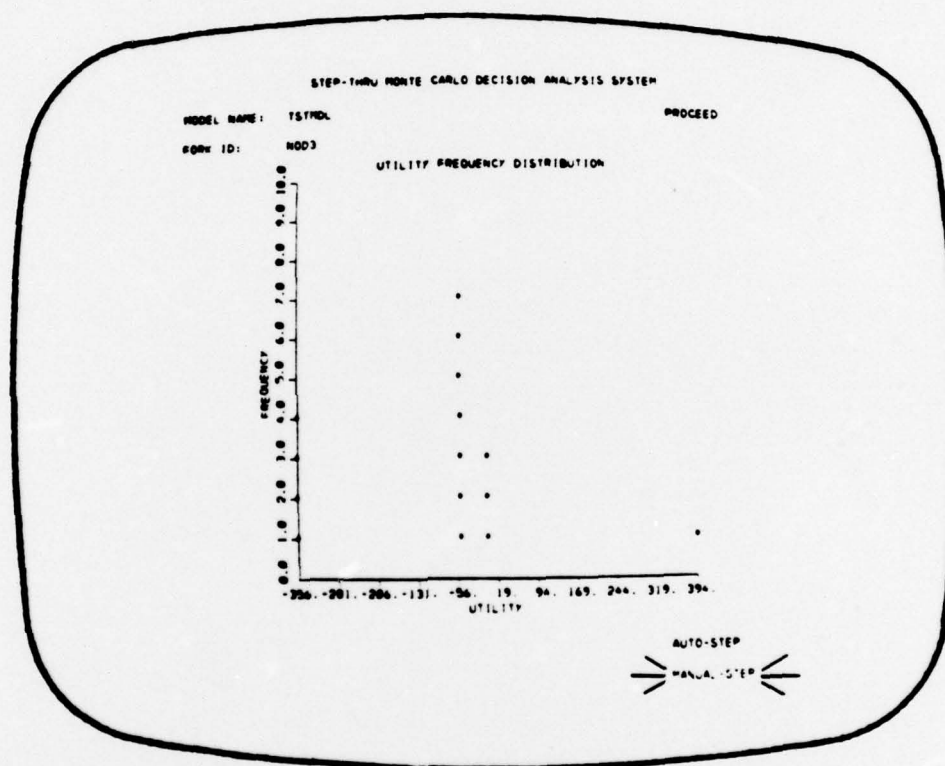

Figure A-13
MONITOR DISPLAY 13

the tree. The abscissa of a star corresponds to the cumulative utility of the path of the trial that it represents. The ordinate corresponds to the number of trials that have resulted in the same cumulative utility. A sample of paths for all of the initial options can be used as a basis for choosing among them, as explained in Section 2.2 above.

A.7 Other Features

The foregoing sections have explained the major features
of the computer program but have omitted the discussions of
how to modify a parameter of a fork (for example, changing
the probabilities on branches of an event fork), retrieve a
model that had been previously defined, purge a model from
the system, modify an existing model, and automatically
process a pre-defined model (without indicating PROCEED at
each step). These topics are not essential to the basic
understanding of the Step-Through variant or its computer
implementation, but may be of interest to a reader who plans
to use the computer program. The interested reader can find
a discussion of these topics in Randall and Barclay (1975).

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